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IMPROVEMENT OF OPERATION OF OPEN-FLAME GLASS-MELTING FURNACES (A REVIEW)

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The paper summarizes the experience of more than ten years of research performed by the authors on industrial glass-melting furnaces of various designs and is based on the analysis of mathematical modeling of heat exchange processes in the flame space of these furnaces. The mathematical modeling is based on the most adequate zonal method for heat exchange calculation. Recommendations for rational organization of combustion of various types of fuel in glass-melting furnaces are supplied.

The nature of heat-exchange processes taking place in glass-melting tank furnaces depends on a great number of simultaneous factors: design specifics of furnaces and burners, the type of fuel, thermal and technological regime parameters, etc.

The conditions of industrial operation of glass-melting furnaces, which, as a rule, operate in non-stationary thermal conditions, make it impossible to experimentally estimate the effect of particular factors on heat exchange. The limited possibilities of experimental research on the heat exchange process and the difficulties in predicting the effect of thermal regime variations on end product quality determined the need for an integrated approach to analysis and refinement of the thermal performance of glass-melting tank furnaces. In the authors' opinion, an effective approach includes the combination of thermal engineering studies of industrial furnaces and the development of mathematical models of heat exchange processes in the working space of these furnaces. In doing so, the purpose of production experiments was fundamentally modified, as the aim of such experiments in this case was to collect data for setting boundary conditions in the developed model, as well as data for assessing the adequacy of the model to the real processes occurring in the thermal system.

The following experimentally found boundary conditions were selected for modeling of the external heat exchange process in the melting zone of the furnace: the surface temperature of furnace enclosures (roof brickwork and wall brickwork), the temperature of the heat-absorbing tank surface (batch heaps, melting foam, and open glass surface), and the thermal regime parameters, i.e., the overall fuel consumption, the air consumption, the distribution of fuel and air among the burners, and the air heating temperature. For the adaptation of the model, the temperature of waste gases leaving the flame space of the furnace was measured, and the data of stationary sensors installed on the furnace to control the thermal regime, i.e., the thermocouples on the roof and the lateral walls of the flame space, were used as well.

The outer surface temperature of the furnace enclosures was determined using a TTTs-1-02 measuring set (a thermoelectric digital thermometer) with the TKhK-803-03 sensor (the measurement range 0 – 450°C).

The temperature of the surface layer of the batch and glass melt was measured employing an immersion thermocouple with carbon block shields [1]. The TPP thermocouple seal was protected with a quartz tip. A secondary tool was the KSP-3 potentiometer with the measurement range 0 – 1600°C. The thermocouple was inserted into the gas space through the openings in the lateral walls at a distance of 1 m from the inner surface. In measuring the temperature on the surface of the melt, the thermocouple tip was immersed to a depth of 10 – 15 mm; in measuring the temperature inside the melt depth, it was immersed to 40 – 300 mm. The measurement duration (35 – 40 sec) was previously determined based on the experimental runaway curve of the measuring set. Two-three measurements were performed at each point.

The heating temperatures of air and waste gases were measured inside the vertical channels at a height around 1 m from the working site level, employing an aspiration thermo-

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couple with TPP thermal electrodes and the KSP-4 automatic potentiometer with the measurement limits 500 – 1600°C. The rate of compressor air consumption by the aspirating ejector was selected in such a way that a further increase in this rate should not affect the data of the measuring set.

The analytical calculations performed employing mathematical models give the basis for the qualitative and quantitative evaluation of a modification of the structural elements of the working space, or significant modification of thermal regimes, which, as a rule, cannot be experimentally implemented in searching for the optimum regimes, as it involves a risk of defects. The reliability of the results obtained in this way depends on the precision of the mathematical description of heat transfer processes in the furnace, accounting for their complex interrelation, and the correct statement of the boundary conditions in the model.

Many well-known domestic and foreign researchers for years have been studying the problem of complex radiant-convective transfer. However, only by the end of the 1960s, were the first variants of the zonal calculation method developed, which made it possible to solve some practical engineering problems. A further development and refinement of the method for the calculation of complex heat transfer was implemented under the direction of Prof. V. G. Lisienko at the Ural State Technical University [2].

According to this method, the working space of the furnace is split into n surface zones and m volume zones, and a nonlinear equation of thermal balance and heat transfer is written for each of them:

$$\sum_{\substack{i=1\\ i\neq j\\ (j=1,2,\dots,n+m)}}^{n+m-1} A_{ij}^{\Sigma}T_i^4 - A_j^{\Sigma}T_j^4 + \sum_{\substack{i=1\\ i\neq j}}^{li} g_{ij}T_i - g_jT_j - Q_j = 0. \quad (1)$$

This form for writing the equation was first proposed by V. G. Lisienko. The first two summands in this equation constitute the resulting radiation heat flow Q_{rj} for the zone j equal to the difference between the heat absorbed by this particular zone j due to radiant transfer from other zones i ($Q_{\mathrm{ab}\,j}$) and the proper radiation of zone j ($Q_{\mathrm{pr}\,j}$), i.e.:

$$\sum_{\substack{i=1\\ i\neq j}}^{n+m-1} A_{ij}^{\Sigma}T_i^4 - A_j^{\Sigma}T_j^4 = Q_{\mathrm{r}\,j} = Q_{\mathrm{ab}\,j} - Q_{\mathrm{pr}\,j}. \quad (2)$$

The third and the fourth summands $\left(\sum g_{ij}T_i - g_j\,T_j\right)$ represent the value of the resulting heat exchange of the particular zone j with the adjacent zones i, as a consequence of heat transfer via the moving medium, convective heat transfer, and heat transfer through surface zones. With this aim, the coefficients of mass exchange and convective exchange between the zones g_{ij} and g_j under the zone temperatures T_i and T_j are introduced in equation (1). The last summand (Q_j) characterizes the amount of heat supplied to zone j from outside. For volume zones, Q_j is equal to the chemical heat emission in a particular zone, and for surface zones, it correlates with the heat transmitted to the zone from outside by heat transfer.

The coefficients A_{ij}^{Σ} and A_j^{Σ} (W/K^4) of radiation exchange between the respective zones, which form part of equations (1) and (2), are calculated using the resolving angle coefficients determined on the basis of the statistical testing method (the Monte-Carlo method) [2].

The zonal method was implemented on the basis of the fundamental research in the flame theory performed at the Department of Thermal Physics and Data Processing in Metallurgy at the Ural State Technical University, which made it possible to express mathematically the variation in the relative aspiration of air for combustion α' and the extent of fuel combustion χ along the flame length, in accordance with the following expressions:

$$\alpha' = \alpha_c\,[1 - \exp(-mnx)];$$

$$\chi = [1 - \exp(-mx^2)],$$

where α_c is the coefficient of air consumption on combustion; m and n are coefficients which are functions of the flame length and are calculated based on the flame spread regularities; x is the distance along the flame length, m.

The zonal method was successfully used for the analysis of heat-transfer processes in glass-melting tank furnaces of various designs [3 – 7]. These studies involved three-dimensional furnace models, which best of all reflect the main specifics of furnace design and flame spread. While composing the geometry of a model, or selecting the scheme of flame spread and gas migration in the work space of the furnace, the choice in each case was based on aerodynamic modeling data obtained on physical models of furnaces, data of experimental thermal engineering measurements, and visual observations of operating furnaces.

The work space configuration for the model was simplified to the parallelepiped shape: the length and the width of the tank were taken in accordance with the sizes of a functioning furnace, and the work space height was taken based on the equality of brickwork extension from the tank surface for the furnace and the model (F_b/F_a = const). In order to take into account the specifics of the position and the spread of the flame (or several flames) with respect to the heat-absorbing tank surface, the arrangement of technological zones on the surface, i.e., melting batch, technological foam, and pure mirror, and the arrangement of the burner inlet openings and the charging hoppers, the working space was arbitrarily split sections into estimate segments along the length, width, and height. The accepted splitting scheme determines the number of volume zones (the flame, combustion products, and glass melt) and the surface zones (the tank, the walls, and the roof), and equation (1) of heat transfer and thermal balance was written for each zone.

The studies encompassed virtually all types of glass-melting tank furnaces provided with heating of combustion air in heat-exchangers, but each case addressed specific technical

problems, mostly related to the upgrade of the heating system of the furnace and the optimization of its thermal regime.

Using the above approach and the mathematical instrument of zonal calculations, the authors developed models of external heat exchange in the flame space with different degrees of detail for the following types of glass-melting furnaces: recuperative furnaces with a double roof, regenerative furnaces with laterally directed flames for sheet and container glass, regenerative furnaces with horseshoe migration of combustion products for melting container glass and silicate materials [3 – 7].

These models in combination with experimental data obtained for existing furnaces were used to calculate heat exchange parameters in studying a wide range of problems related to the performance of glass-melting furnaces.

Here are some specific examples.

A direct-flow recuperative furnace is designed for melting aluminoboron silicate glass used in production of fiberglass (Valmiere Fiberglass Factory, Latvia). The approximated zonal model of its work space is shown in Fig. 1. Using this model, the effect of the flame length and luminosity was studied in relation to using mazut, kerosene, and natural gas as fuel [8]. A relationship was established between the furnace efficiency, the thermal load, and the glass melting temperature. At increased melting temperatures (1500 – 1600°C), an increase in the furnace efficiency requires substantially less thermal energy consumption than at lower process temperatures (1300 – 1400°C). Taking into account the earlier studies of an operating furnace [9], the heating system of this furnace was upgraded: the number of atomizers located under the burner entry was reduced from six to four, and the fuel supply via the edge and the middle atomizers was differentiated (40 and 60% respectively). Later on, using a specially developed zonal model [10], an analytical calculation assessment of the proposed method for heating the recuperative furnace was performed, which fully corroborated the expediency of this method. It was found that the optimum flame length should not exceed 0.25 of the length of the furnace working space.

The implementation of these measures provided for a more uniform distribution of thermal flows over the tank surface, good quality of the resulting glass melt, and a high efficiency of the furnace.

Figure 2 represents a zonal model of the melting zone of a furnace with lateral arrangement of flames (Salavatskii Technical Glass Factory). Similar furnace models, although with a smaller number of burners (three pairs of burners in each) were developed for the Mineralovodskii [5], Irbitskii, and Ufimkinskii glass factories. In each specific case, the multizonal heat-exchange models made it possible not only to perform a detailed analysis of the thermal state of particular elements of the working space brickwork, but to evaluate the most rational thermal load distribution among the burners, and to ensure optimum conditions for the glass-melting process. It was established that the optimum flame length for multi-flame furnaces of this type should be equal to

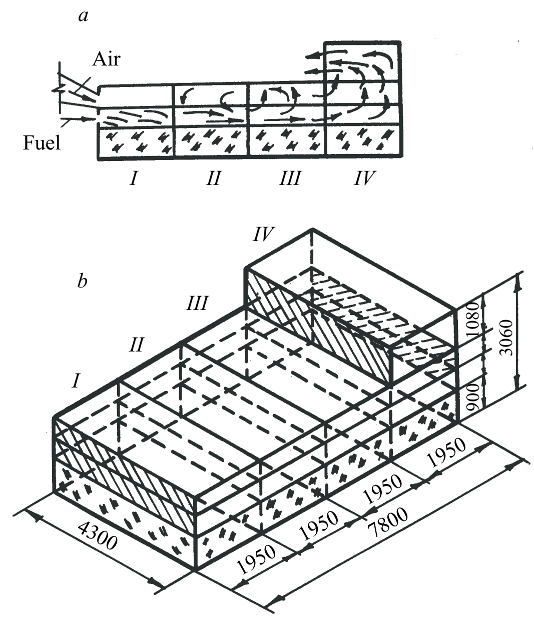

Fig. 1. Scheme of gas migration in glass-melting furnace with a double roof (*a*) and approximated zonal model of the working space of this furnace (*b*) split into calculation segments *I* – *IV*.

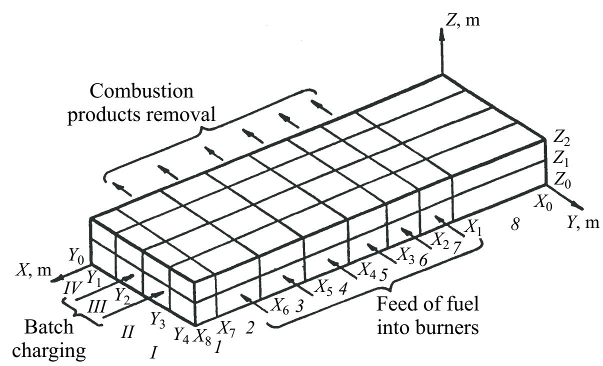

Fig. 2. Zonal model of the melting zone of glass-melting furnace for sheet glass: *1* – *8* and *I* – *IV*) number of calculation segments along the tank length and width; X_i, Y_i, Z_i are the coordinates of zonal boundaries.

0.50 – 0.75 of the tank width. This provides for the maximum integral heat absorption and for better uniformity of the field of density of the resulting specific heat flows on the tank surface [11].

The calculation analysis carried out using a specially developed zonal model of a working space segment corresponding to one pair of burners [12] made it possible to make a comparative evaluation of different methods for introducing fuel into regenerating air flow: upper feeding when air is fed to the burner cheeks, and lower feeding when air is fed underneath the burner entry. The efficiency of the lower feeding method was demonstrated, and the conditions for achieving this efficiency were formulated.

Figure 3 shows the spatial scheme of the zonal model of a container glass-melting furnace with a horseshoe-shaped

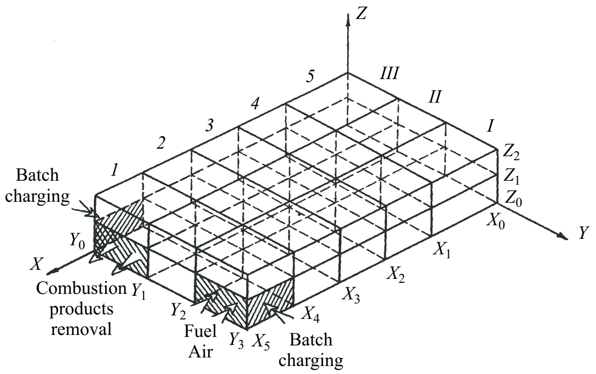

Fig. 3. Zonal model of the melting zone of container glass furnace with horseshoe flame direction: *1 – 5* and *I – III*) number of calculation segments along the tank length and width; X_i, Y_i, Z_i are the coordinates of zonal boundaries.

flame direction (Mineralovodskii glass factory). A similar model with similar splitting into zones was used to analyze heat-exchange processes in a furnace for silicate material melting (Chelyabinsk Factory of Solid Mineral Wool Tiles).

The aim of the research was to find resources to intensify the thermal and technological processes and, at the same time, to solve the problem of the tank brickwork resistance. The optimum flame length for a furnace of this type should be 0.7 of the working space length. It was found that in the absence of combustion intensifiers and the existing resistance limitations of the flame space brickwork, adequate melting of the batch can be accomplished through intensification of the furnace operation. In order to intensify glass melting, the tank design should provide for a well extended scheme of glass melt convection flows, and the more extended the flow scheme, the higher the melting intensity [13]. Obviously, the rational organization of fuel combustion in the flame space of the furnace has the dominant role in solving this problem.

The experience accumulated by the authors indicated that the developed models adequately reflect the real processes of complex heat exchange in the considered furnaces and can be effectively used for detailed studies and prediction of the thermal performance of the furnaces.

The obtained information on thermal processes reflects much more fully and reliably the real situation inside the melting space, than the most thorough measurements performed in operating furnaces. The latter are needed to obtain data on the current state of the furnace, and these data are used as boundary conditions in mathematical modeling.

The main object of study in the quoted papers is the external heat transfer in the working space of the furnace. The possibility of solving the problem of external heat transfer allows for a more well-founded approach to the problems of internal heat transfer (batch melting process, glass melt heating, organizing convective melt flows, etc.).

Further modifications in designs and thermal regimes of glass-melting furnaces intended to improve the product quality and the efficiency of thermal performance undoubtedly call for research of the operation of tank furnaces. Significant achievements in this field were accomplished by the American school headed by Prof. R. Viskanta [14]. We believe that considerable progress could be achieved by synchronizing the research in the field of the external and the internal heat-transfer problems with respect to glass-melting furnaces, which would require the application of up-to-date computer hardware and the development of synchronic software. This appears as a prospect for further research which will finally lead to the development of a scientifically substantiated approach to the problem of monitoring and controlling thermal and technological processes in glass-melting tank furnaces.

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